On Dynamic Wavelength Switching of SG-DBR Lasers for Wavelength Routing Applications

by

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Submitted to the Department of Physics in partial fulfillment of the requirements for the degrees of

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Abstract

The use of WDM can increase transmission capacities of optical fibre networks by utilizing multiple wavelength channels per fibre. To make better use of this ever-increasing bandwidth and to build systems that are more suitable for data-dominant network, packet switching has to be implemented. Issues concerning the deployment of optical packet switching will be discussed and wavelength routing based on tunable semiconductor lasers is studied. Switching speed of tunable lasers is an important parameter indicating applicability of the system thus wavelength switching dynamics of SG-DBR lasers is investigated. Wavelength switching speed and intermediate mode suppression ratio were measured on two SG-DBR laser with different gain geometry. Pulse pre-distortion technique is then studied, and demonstration was made that it help enhance wavelength switching, both in terms of speed and intermediate mode suppression.

Thesis supervised by

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Chapter 1

Introduction

1.1 Optical Fibre Communication

Optical fibre communication had a big push forward at the emerge of wavelength division multiplexing. (WDM) The ability to utilize multiple wavelength channels per fibre had allow capacity per fibre to increase by order of magnitude, and in some cases even without installing new fibres into the ground. The second boost had come from the development of Erbium-doped fibre amplifier (EDFA), which extended the distance-without-regenerator from about 50 km to hundreds of kilometer. Number of wavelength channels in WDM networks is constrained by amplifier gain bandwidth, demultiplex capability, and nonlinear effects.

Together, WDM and EDFA provided mean for long distance, high capacity signal transmission, and had allow wide spread deployment of optical telecommunication system by making them more cost-effective.

However, as internet traffic grows at its amazing speed, anticipations had it that data traffic will grows over voice traffic in near future. Data usually comes in small blocks called packet, and transporting these packets over existing telecommunication networks had been an issue under consideration during the past few years. Currently packet data were transported on existing circuit-switched network via multiple layers of protocol. (Figure 1-1) This is complicate and inefficient, and optical packet switching leading to packet-over-WDM networks had been given much interest in recent years.

8
1.2 Organization of the report

It is the aim of this project to address issues involved with optical packet switching, in particular the switching speed. Wavelength routing looks very promising in providing the required performances for packet switching. For this, a tunable transmitter capable of providing high precision of wavelength controlling and fast switching between wavelengths is required. Dynamic wavelength tuning characteristics of SG-DBR lasers will be investigated, thus giving insight on how viable this kind of device is for wavelength routing and, ultimately, optical packet switching.

1.2 Organization of the report

This report is organized as followed: Chapter 2 discuss optical packet switching, issues needed to be consider in packet-switched networks e.g. contention resolving and packet format, and wavelength routing. Chapter 3 presents various types of tunable semiconductor lasers, tuning mechanism, and performance comparison between them. SG-DBR lasers will be discussed in more detail as it is the device investigated in this project. Next, Chapter 4 presents studied tuning dynamics of SG-DBR lasers and implication to its applicability in wavelength routing.
Chapter 2

Optical Packet Switching

It is anticipated that the rapidly growing data traffic will overcome voice traffic in near future. More and more interests have thus focussed on development of packet switched networks to accommodate future traffic. In today’s networks, packet data are carried on circuit switched networks through multiple levels of protocol, and performances are not optimized. It is desirable to have true packet switched networks transmitting packet-over-WDM and this chapter will discuss relevant issues that arise when optical packet-switched networks were studied.

2.1 Packet versus Circuit

In packet switched systems, data are split into small "blocks" called packets and send independently to the destination, where they will then combine seamlessly to give the original information. Packet switching offers many advantages over circuit switching, most importantly efficient channel sharing, and thus cost effectiveness.

Unlike circuit switched system, no channels were dedicated to any connection in the network and multiple users can share the available bandwidth, resulting in lower cost per bit. An insightful way of representing this is the highway model. (Figure 2-1) In this analogy, wavelength channels are represented as lanes of highway and data flow as cars on the highway. In circuit switched networks, number of channels required equals number of connection between hosts, and can also results in wasted bandwidth such as the B-E
connection in upper highway of Figure 2-1. These problems can be overcome by having all the channels accessible to every host as in lower highway of Figure 2-1. The network resources are used more efficiently and the number of required channels is reduced.

Packet switched networks are, however, more technologically demanding and more difficult to deploy. One very important requirement on such networks is the ability of switches to route data on packet-by-packet basis, which means ultra-fast switching is required. (see Table 2.2.1)

2.1.1 Optical versus Electrical Switching

In currently deployed networks, packet data are switched electronically, which means data has to be converted from optical to electrical form, passed through appropriate switch, then converted to optical again for retransmission. Electrical packet switching offers great potential, but is ultimately limited by processing capability of electronic devices, and in
2.2 Packet Switched Networks

2.2.1 Switching Speed

Packets varied in size depending on specific application and protocols, but it can be said that in general switching speed required is of the order of nanoseconds. Table 2.1 shows switching time available for one kind of packet, namely ATM cells, at different line rate. Faster switching is required for higher line rate. A study by [1] indicates that, for a successful optical packet switching, the laser switching time should not be less than or of the order of 10% of the available processing time. It has to be noted that this is conclusion based on only one scheme of packet switching, namely "carrier sense multiple access with collision avoidance", or CSMA/CA.

This ultra-fast switching speed requirement is obviously more difficult to achieve than in circuit switched networks, which, for example, would need switching time of the order of millisecond for protection switching. (Figure 2-2) Switches reconfiguration time of hours or days is not uncommon for current optical networks, packet switching will require this to reduce to sub-microsecond.

Table 2.1: Available ATM Cell Processing Time as function of transmission bit rate [2]

<table>
<thead>
<tr>
<th>Signal</th>
<th>Line Rate</th>
<th>ATM Cell Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>STM-1</td>
<td>155.5 Mb/s</td>
<td>2.73 $\mu$s</td>
</tr>
<tr>
<td>STM-4</td>
<td>622 Mb/s</td>
<td>682 ns</td>
</tr>
<tr>
<td>STM-16</td>
<td>2.5 Gb/s</td>
<td>170 ns</td>
</tr>
<tr>
<td>STM-64</td>
<td>10 Gb/s</td>
<td>43 ns</td>
</tr>
</tbody>
</table>

many circumstances will form an *electrical bottle neck* in optical networks. Speed of optical switching had yet reach its limit, but it is already clear that much faster switching can be achieved.

Switchings performed solely in optical domain are sometimes called *All-Optical-Switching* to contrast with switchings done in electrical domain.
2.2. Packet Switched Networks

2.2.2 Packet Synchronization

Packet switched networks can be divided into two categories: synchronous and asynchronous networks. In synchronous network, packets coming into each nodes were align in time and then switched. This kind of network will perform best with packets of equal length. On the other hand, asynchronous networks may have packets of different lengths coming in and out of nodes without being aligned.

Asynchronous networks are more easy and cheap to develop as there is no need for synchronization of network as a whole, and is also more open to various format of packets. They are, however, less efficient comparing to synchronous networks and contention can occurs more easily as it is difficult to buffer packets of non-uniform sizes and switching fabrics can only be re-adjust at discrete times. There is a trade-off between performance and simplicity and whether synchronous or asynchronous system is better is still unclear.

2.2.3 Contention Resolving

Contention occurs when two or more packets need to be routed to the same output port at the same time, obviously this cannot be accomplished. There are currently two ways to
handle this situation, one is to use some kind of buffer to store all but the highest priority packet, wait until that packet got through, then route packets that were kept hold. [3,4] The second method is to send those lower priority packets to the wrong address, which will in turn attempt to route them to the correct destination, this is called Deflection Routing. [5] There also exist hybrid method using both buffering and deflection routing [6], that is have some buffers but if data overflows occur, deflect lower priority packets to incorrect output to try to reroute itself.

Buffering can be done easily in electrical domain using random access memory (RAM) which can be read/write at any time. In optical domain, however, there is no method of storing photons, packets thus need to be put through some delay line with appropriate length, which has to be calculated before buffering taken place. Achieving desired delay for each packet is key for contention resolving and also for packet synchronization at the input of nodes in synchronous networks. Various buffering schemes were reviewed in [7], performance on packet loss rates, bit error rates were also provided.

2.2.4 Header & Packet Format

Currently, the most promising method to incorporate header\(^2\) with its packet is to use subcarrier multiplexed header. This is done by encoding header on subcarrier frequency on the same channel as the its payload, at lower bit rate. The header can then be retrieved by detecting fraction of incoming signal with conventional photodetector and filter. This is far more superior than encoding header at the same bit rate as its payload, as electronic processing at such high bit rate is difficult to implemented. Subcarrier multiplexed header also has advantage that dispersion between header and payload is very small, comparing to other header format which encoded header on separate wavelength. (The latter has, however, advantage when header needs to be re-write at each network nodes)

Packet length is another important parameter to considered. Higher packet-to-header size ratio means more throughput because greater percentage of bandwidth is actually used to transport data. On the other hand, too long packet suffer from the need of longer buffer

\(^2\)Headers are information used to identify origin, destination, and nature of individual packet. Each packet contains header and the carried information, or payload.
and inefficient packet filling. (the latter is of course, only a problem with fixed-length-packet format)

Currently, different packet types (e.g. IP, ATM, frame relay) contain different header of different lengths and format. This means each type of packet needs its own kind of switch, and processing time is wasted as major part of the header contains irrelevant information regarding transportation of the packet in networks. Tag switching is proposed to solve this problem. This involve assigning short, fixed length tag to multi-protocol packets solely for transport purpose and let switchings occur at tag level. This would increase transparency in the network and reduce packet processing time.

### 2.3 Switching Fabrics

This section presents and compares performance of various optical switching fabrics available. These performance figures change very rapidly and effort had been spent to ensure they are correct and up-to-date at the time of print.

MEMs based switching fabric had thus far received most study and many commercial products had been announced to date. MEMs bases switches offer satisfactory performance (good extinction ratio and high number of port) but the fact that this technology base on electro-mechanical parts means that ultra-fast switching is hard to achieved. Switches based on other fabrics also offer inadequate switching speed for optical packet switching, except for tunable lasers with wavelength router. This might also offer higher reliability as passive
routers are used and switching depends on more well-understood optoelectronic phenomena. Next section discuss optical switching based on tunable transmitter and passive wavelength router, usually called *Wavelength Routing*.

One key property of ideal switch is scalability. To be able to upgrade/expand capacities to cope with increased traffic is compulsory in many applications and therefore modular switch with future upgradability is needed. Different technologies might need totally different implementation to allow this modularity and further studies are needed in the area of efficient integration of switch modules.
### Table 2.2: Comparison of optical switching fabrics

<table>
<thead>
<tr>
<th>Switching Fabric</th>
<th>Mechanism</th>
<th>Number of port</th>
<th>Switching speed</th>
<th>Key players</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Crystals</td>
<td>Rotate polarization state according to applied current</td>
<td>up to 8 X 2 [9]</td>
<td>milliseconds</td>
<td>Chorum Technologies Inc. Corning Inc. Spectraswitch, Inc.</td>
</tr>
<tr>
<td>Tiny Bubbles</td>
<td>Bubbles alter light paths (use inkjet technology)</td>
<td>32 X 32 module (scalable)</td>
<td>milliseconds</td>
<td>Agilent Technologies Inc.</td>
</tr>
<tr>
<td>Thermo-optical switches</td>
<td>Heating change refractive index, thus light paths</td>
<td>up to 8 X 8</td>
<td>1 millisecond</td>
<td>JDS Uniphase Inc. Many others</td>
</tr>
<tr>
<td>Tunable Lasers</td>
<td>Tunable lasers and wavelength specific devices (e.g. AWG³)</td>
<td>up to 256 X 256 [10]</td>
<td>nanoseconds</td>
<td>Agility Communications Altitun AB Coretek, Inc. Marconi PLC</td>
</tr>
</tbody>
</table>

1 Arrayed Waveguide Grating, see Appendix A for more detail.
2.4 Wavelength Routing

Wavelength routing utilize tunable transmitter and wavelength specific router to direct signal from input to output ports. The desired router should be able to directs signals according to their input port number and wavelengths. It will also need to be manufacturable with large number of port, have miniature dimensions, and preferably easy to integrate with other components. One type of router offering such performance is arrayed waveguide grating (AWG). Figure 2-4 shows schematically how wavelength routing can be accomplished.

It is obvious that well defined and controlled wavelength is important to make this scheme works, as failure of tunable transmitters to deliver such performance would result in data being lost or routed to incorrect output port. Wavelength controlling will be discussed further in Section 3.4

Figure 2-4: Wavelength routing scheme based on tunable lasers
Various scheme of packet switching by wavelength routing had been proposed [1, 11, 12, 13, 14, 15] and discussed [16], various demonstrations had also been done. [12, 17, 18, 19, 20, 21] To date, number of nodes in these demonstration are up to 8 and using 6 wavelengths. Preliminary results are promising while more works are still needed to show that these systems will work on larger scale.
Chapter 3

Tunable Semiconductor Lasers

This section will start by discussing roles played by tunable lasers in optical communication. From this, performance requirements can be drawn and in later sections it will becomes clear what applications are viable for each type of tunable semiconductor lasers.

As carriers deploy more narrow wavelength grid in WDM network, and broader band optical amplifiers are being studied, number of wavelength used in WDM system will continue to increase. The number of wavelength can expect to rise to 80 or higher within five years. With this increasing in number of wavelength, and thus number of lasers required, stocking backup for each individual laser is not cost effective and this is where tunable lasers can play a major part. With ability to access many wavelengths, one tunable laser can act as replacement for number of, or even all, lasers in the network, thus greatly reduce the cost for inventories and storage.

With the predicted decrease in price of tunable lasers, it could be possible to replace all conventional DFB lasers with tunable lasers, so that the same drive & control system can be use for both working and backup lasers. For tunable lasers to dominate the market as WDM light source, many issues have to be addressed, including wavelength locking, effects of aging and the currently low output power compared to DFB lasers.

Other applications of tunable lasers include wavelength references in WDM networks, application in sensing e.g. optical radar and spectroscopy, and application in optical measurements e.g. fiber characterization and spectrum analysis. These applications will not be discussed further here, interested readers are referred to Amann and Buss [22] for a
3.1 Tuning mechanism

Before discussing tunable laser geometries, it should be noted that even though these lasers employed very different method to achieve wavelength tuning, the basic physical processes are the same. Tuning mechanism therefore deserved to be discuss here in detail. There are three general wavelength tuning method for semiconductor lasers, namely Carrier injection (or free carrier plasma effect), quantum confined Stark effect (QCSE), and temperature tuning. Theoretical treatment on each types of tuning will not be present and readers are referred to page 84-92 of [22]. Tuning performance comparison of these mechanisms is shown in Table 3.1. Note the difference in sign of wavelength change between temperature tuning and the other two mechanisms.

Among these, carrier injection is most widely used for tunable semiconductor lasers, as it offered broadest tunability. Temperature tuning is indirectly involved here as injecting current into materials will generate heat which in turn raise the temperature and affect emitting wavelength. Sign of wavelength change of the two mechanism are different so thermal effect will reduce tuning efficiency if suitable control of temperature is not presented.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Carrier Injection</th>
<th>QCSE</th>
<th>Temperature Tuning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta n$</td>
<td>-0.04</td>
<td>-0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>0.5</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>$\Delta \lambda$</td>
<td>-8 nm</td>
<td>-1 nm</td>
<td>+5 nm</td>
</tr>
<tr>
<td>$\alpha_H$</td>
<td>-20</td>
<td>-10</td>
<td>large</td>
</tr>
<tr>
<td>Heat generation</td>
<td>large</td>
<td>negligible</td>
<td>very large</td>
</tr>
<tr>
<td>Technology</td>
<td>moderate</td>
<td>demanding</td>
<td>simple</td>
</tr>
</tbody>
</table>

Table 3.1: Comparison of electronic tuning mechanism of tunable semiconductor lasers. Parameter presented are refractive index change $\Delta n$, Confinement factor $\Gamma$, Wavelength change $\Delta \lambda$, phase-amplitude coupling factor $\alpha_H$, level of heat generation, and implementation difficulties. Values shown are for practically achievable devices. (Reproduced from [22])

3.1 Tuning mechanism

comprehensive overview of application of tunable semiconductor lasers.
3.2 Tunable Laser Geometries

Following subsections discuss briefly on commonly-known types of tunable semiconductor lasers, note that four out of five geometries are based on DBR lasers, with different enhancements of tuning technique. This section is intended to provide rough ideas of the different geometries and characteristics. Readers are referred to references given in each section for more detail on each laser type e.g. detailed spectral properties and tuning mechanisms. A very good account on tunable lasers can be found in Amann and Buus [22].

3.2.1 Distributed Bragg Reflector (DBR) lasers

Invented in early 1980’s, this is the most basic type of laser discussed here, yet providing highest output power. For carrier- injection tuned DBR lasers, the maximum fractional tunability satisfied the relation

$$\frac{\Delta \lambda}{\lambda} = \Gamma \frac{\Delta \mu}{\mu}$$

(3.1)

where \(\lambda\) is the central wavelength, \(\Gamma\) is the confinement factor and \(\mu\) is refractive index of the material. For InP-InGaAsP device, this limit the electronics tuning range to about 10 nm [23] at 1.55 \(\mu\)m. This does not cover the amplifying band of EDFA and therefore tunable DBR laser is not ideal as tunable light source for WDM. This tuning range is, however, much smaller than the gain bandwidth of the laser itself. (about 100 nm) It is therefore interesting to see how the limit on tuning range imposed by Equation 3.1 can be overcome in the following three types of laser.
3.2. Tunable Laser Geometries

CHAPTER 3. Tunable Semiconductor Lasers

3.2.2 Sampled Grating - Distributed Bragg Reflector (SG-DBR) lasers

First proposed in 1990 [24], SG-DBR is the one of the first widely tunable laser available. [25] The narrow tuning range of DBR lasers is overcome by having two, instead of one, grating sections in the structure, with grating in each section removed in periodic manner, and grating period slightly different. As will be discussed further in Section 3.3, this structure provides a wider tuning range by utilizing vernier-like effect of reflection peaks of the two grating sections.

Manufacturing process of SG-DBR lasers is very similar to that of DBR lasers, only additional masks were needed to generate the interrupted grating. This is a big advantage as manufacturing facilities for DBR lasers are readily available.

3.2.3 Super Structure Grating - Distributed Bragg Reflector (SSG-DBR) lasers

Sampled grating implemented in SG-DBR lasers can be considered as special case of a more general structure, namely super structure grating, with sampling function regarded as modulation function on a uniform grating. Different modulation function would give different shape of envelope of the reflectivity peaks. One well known type of super structure is the linearly chirped grating, as shown in Figure 3-3. Shape of the reflection envelope depends on fourier components of the modulating function, thus suitable synthesis of modulation function can, in principal, generate any desired shape of envelope. (the obtained structure might be, however, impractical to build) Obviously the ideal shape of reflection envelope is rectangular, and this had been demonstrated in [26].
3.2. Tunable Laser Geometries

Figure 3-3: Super structure grating DBR lasers with linear chirped grating

Figure 3-4: Grating coupled - sampled reflector (GCSR) laser

3.2.4 Grating Coupled - Sampled Reflector (GCSR) lasers

This laser structure employed two technology to provide wide tuning and good spectral selectivity, one is grating assisted coupler, and the other is sampled grating reflector. [27,28] The idea behind is to match the reflection peak spacing of the sampled grating to the filter width of grating assisted coupler.

3.2.5 Vertical Cavity Self Emitting Laser (VCSEL) lasers

VCSEL is totally different from the discussed tunable laser geometries as it is not based on DBR lasers, and tuning mechanism is very different. VCSEL emit light perpendicular to the p-n junction and tuning can be achieved by temperature tuning or by moving the top mirror using micro-electromechanical machine.

One advantage of VCSEL lasers is that their relatively short active medium means only one longitudinal mode experience gain. Thus VCSEL guaranteed single mode and continuous tuning characteristics. Tuning, however, is quite slow in VCSEL resulting from thermal or micro machine based tuning technique.
3.2. Tunable Laser Geometries

CHAPTER 3. Tunable Semiconductor Lasers

Figure 3-5: Vertical cavity self emitted laser

<table>
<thead>
<tr>
<th>Laser type</th>
<th>Tuning range</th>
<th>Output power</th>
<th>Switching time</th>
<th>Manufacturing difficulty</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBR</td>
<td>10 nm</td>
<td>10 mW</td>
<td>&lt; 10 ns</td>
<td>easy</td>
</tr>
<tr>
<td>SG-DBR</td>
<td>&gt; 35 nm</td>
<td>2 mW</td>
<td>&lt; 10 ns</td>
<td>moderate</td>
</tr>
<tr>
<td>SSG-DBR</td>
<td>&gt; 35 nm</td>
<td>1 mW</td>
<td>&lt; 10 ns</td>
<td>hard</td>
</tr>
<tr>
<td>GCSR</td>
<td>40 nm</td>
<td>1.5 mW</td>
<td>&lt; 10 ns</td>
<td>hard</td>
</tr>
<tr>
<td>VCSEL</td>
<td>&gt; 35 nm</td>
<td>&lt; 2 mW</td>
<td>ms</td>
<td>hard</td>
</tr>
</tbody>
</table>

Table 3.2: Characteristics of various type of tunable semiconductor lasers, compiled from [29]

3.2.6 Comparison for packet switching application

Table 3.2 compares the discussed types of tunable laser in terms of important properties regarding packet switching. A tradeoff between tuning range and output power can be seen. It is quite obvious that DBR and VCSEL lasers are not suitable for WDM packet switching due to narrow tuning range and slow switching, respectively. For the other three types of laser, SG-DBR, SSG-DBR, and GCSR, the operating properties are very similar, with GCSR lasers having somewhat broader tuning range. However, the relatively easy to manufacture SG-DBR lasers should prove to be successful when it comes to mass production. This means that it will be cheaper and faster to produce. SG-DBR lasers will be discuss in more details in Section 3.3.

Note that Table 3.2 only shows performance of lasers that are practically achievable, or
3.3 Sampled Grating DBR Lasers

Tunable semiconductor lasers investigated in this project all belong to this category. Hence it deserved further discussion on various characteristics. In this section its tuning mechanism and spectral property will be discuss in detail.

Sampled Grating DBR (SG-DBR) lasers have structure consists of three or four sections, namely gain section, front and rear grating sections, both host sampled grating. Sampled gratings are grating which had been removed in a periodic manner, as shown in Figure ????. Structure of sampled grating can be identified by following parameters, grating pitch $\Lambda$, grating length $L_g$, and sampling period $L_s$. Quasi-continuous wavelength tuning can be achieved using the above three sections, while phase section provide and easy way to fine tuning, by changing the effective cavity length of the laser.

Reflection spectra of sampled gratings have comb-like structure, as in Figure 3-7. It will be shown in subsequent sections that these comb separations depend on sampling period of sampled grating. By implementing slightly different sampling period in front and rear grating section, different reflection peak separation can be achieved. (Figure 3-8) The relative position of these reflection combs can be altered by carrier injection (thus changing the refractive index), and vernier-like effect can be apply to provide wide tuning range. (Figure 3-9) This is to be discuss further in Section 3.3.2.

SG-DBR lasers (and also DBR, SSG-DBR, and GCSR) can be monolithically manufactured thus enable integration with other key components [30], e.g. EA (Electro-absorbtion) modulator [31, 32, 33], arrayed waveguide grating (AWG) [34], and wavelength monitor [35, 36].
3.3. Sampled Grating DBR Lasers

CHAPTER 3. Tunable Semiconductor Lasers

3.3.1 Reflection properties of sampled grating

The discussion here followed those in [25] with slightly different notation. Sampled grating is nothing more than uniform grating which is interrupted in periodic manner. The sampled grating function can be written as product of uniform grating function and periodic modulation function. The reflectivity of this structure can be then obtained from coupled-mode equations. One prediction from coupled-mode theory is that every spatial Fourier component of the refractive index perturbation give rise to a peak in reflection spectrum. [37] Fourier transform of sampled grating can be obtained by convolving fourier transform of uniform grating and the modulation function. As shown in Figure 3-6, this results in a comb of fourier components centered at Bragg component of the uniform grating.

Figure 3-6 shows sampled grating structure with grating of pitch and length \( L_g \), with sampling period \( L_s \). Fourier components of sampled grating can be written as

\[
f_n = f_0 \frac{L_g}{L_s} \text{sinc}(n \pi L_g/L_s)e^{i \pi n L_g/L_s}
\]  

(3.2)
where $f_0$ is Bragg wavelength of the uniform grating.

Reflection strength at each fourier component increases with coupling strength $\kappa_n$, which is proportional to the fourier component itself. Coupling coefficient of each fourier component of sampled grating can be written as

$$\kappa_n = \kappa_0 \frac{L_g}{L_s} \text{sinc}(n\pi L_g/L_s)e^{i\pi n L_g/L_s}$$  \hspace{1cm} (3.3)

where $\kappa_0$ is coupling strength of uniform grating.

A uniform grating with coupling strength $\kappa$ has reflectivity given by [38]

$$r(\lambda) = \sum_n \frac{i\kappa_n \text{sinc}(q_n L_{sg})}{q_n \cos(q_n L_{sg}) - i\Delta \beta_n \sin(q_n L_{sg})}$$  \hspace{1cm} (3.4)

where

$$\Delta \beta_n = \frac{2\pi \mu(\lambda)}{\lambda} + \frac{i \alpha}{2} - \frac{\pi}{\lambda} - \frac{\pi n}{L_s}$$

$$q_n^2 = \Delta \beta_n^2 - |\kappa_n|^2$$

$L_{sg}$ = length of sampled grating structure

Putting Equation (3.3) into (3.4), reflectivity of sampled grating structure is obtained. This result is shown schematically in Figure 3-7.

Following characteristics of reflectivity in Figure 3-7 can be deduced from Equation (3.3) and (3.4):

Peak power reflectivity of the $n^{th}$ order can be written as

$$R_n = \tanh^2(|\kappa_n| L_{sg})$$  \hspace{1cm} (3.5)

The spacing between reflection peaks is given by

$$P = \frac{\lambda^2}{2\mu_g L_s}$$  \hspace{1cm} (3.6)
where $\mu_g$ is the group index.

Bandwidth of the $n^{th}$ peak is given by [25]

$$\Delta\lambda_{n,bw} = \frac{\lambda^2}{\pi\mu_g} \sqrt{\kappa_n^2 + (\pi/L_{sg})^2}$$

(3.7)

It is shown that reflection peak separation is a function of sampling period $L_s$, thus by employing slightly different $L_s$ in front and rear grating and overlapping combs can be obtained, as shown schematically in Figure 3-8

### 3.3.2 Vernier effect

As shown in Figure 3-8, reflection curves of grating sections of SG-DBR lasers have comb-like characteristics, with slightly different pitches. This can be used to extend the tuning range of the laser, as illustrated in Figure 3-9. By shifting position of one comb by $\delta\lambda$, the pitch difference, the wavelength of incidence shifts by $\Delta\lambda$, the pitch of the other reflection comb. This means the tuning efficiency is enhanced by a factor of $\Delta\lambda/\delta\lambda$ from the limit imposed by Equation 3.1.

This tuning by Vernier-like effect also means that wavelength will jump in step during tuning. However, by shifting both reflection combs simultaneously, access can be gained to
3.3. Sampled Grating DBR Lasers

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Figure 3-8: Reflection combs of front and rear grating section of SG-DBR lasers (Reproduced from [22])

Figure 3-9: Vernier effect of reflection combs of SG-DBR lasers. Showing reflection peaks of front and rear grating, $R_1$ and $R_2$, reflection pitch $\Delta \lambda$, and pitch difference $\delta \lambda$. (Reproduced from [22])
every wavelength within the range, although not in a continuous way. (See for example, Figure 3-10)

Shifting of reflection combs as described above can be achieved by injecting carrier into grating sections, as was described in Section 3.1

3.3.3 Wavelength tuning characteristics

Figure 3-10 shows example of static wavelength tuning map of SG-DBR lasers, note the fan-like mode characteristics. Each fan is dubbed supermode while the longitudinal modes within each fan is called just a mode. Another characteristic worth notice is that tuning is not continuous, as shown in Figure 3-11.

One major obstacle preventing wide spread use of tunable lasers at present time came
from the fact that each and every single laser fabricated has different tuning characteristics, and thus needed to be characterized individually. The reason for this is the slight variation across each laser chip during manufacturing process. These variation, although very small, can cause noticeable effects on wavelength tuning characteristics.

This problem causes two main problem in implementation of tunable lasers. First, the characterization process can took a long time. This problem has become less significant as the technology matured, and characterization time was reduced from days of even week down to a few hours. A new startup company, Intune Technologies [39], had focussed on improving this characterizations process and claims it could take only about 10 minutes in the future.

Another problem is the control system. With different tuning characteristics, each laser has to be incorporated with its own wavelength lookup table. It is impractical to have high resolution lookup table for each lasers, as the lookup process could be too slow, and with effects of aging the table could not maintain accurate correspondence to the laser.
3.4 Wavelength Stabilization

This section discusses shortly the issue of wavelength stabilization, referencing, and monitoring of tunable lasers. Whether tunable lasers are to be used as light sources or as part of switching fabric, one very important problem that has to be address is wavelength stabilization. Like other semiconductor devices, tunable lasers degrade over time and need to be monitored to ensure perfect functionality over its lifetime. The effects of aging in tunable semiconductors is, however, not yet fully understood and companies are doing life tests to see how much and in which way these lasers degrade with time.

For WDM applications, the most important characteristics of laser aging is the wavelength shift over time. It is required that the wavelength shift be much smaller than the channel spacing of the system to avoid crosstalk. Other aspects of aging such as increased threshold current are more tolerable.

Life time requirement for light source in telecommunication system is about 25 years, and during that time conventional DFB lasers have wavelength drift of up to 0.25 nm. Tunable lasers have much more sophisticated spectral properties and to quantify the effects of aging on wavelength shift is not clear cut.

One method to maintain wavelength precision during lasers life time is to lock the wavelength to some kind of filter. Tunable lasers can operate on any wavelengths within its tuning range, but telecommunication standards give the set of wavelength to be used as evenly spaced grid in frequency. It is thus possible to use ethalon filter with suitable cavity length to provide comb-like transmission spectra coincide with the frequency grid.

Analysis was given in [26] on wavelength stabilization of SSG-DBR laser. (As described above, SG-DBR can be considered special case of SSG-DBR)

A practical implementation of such filter would be to detect small amount of light from the laser with two detector, one with filter fitted in front. This way the variation of power due to wavelength drift can be identify from power variation of the laser itself, which could occur from aging.
Chapter 4

Wavelength Tuning Dynamics

Measurements had been done on dynamic tuning characteristics of SG-DBR lasers, using bare laser chip the wavelength switching time was shown to be a few nanosecond. [41] In this project, wavelength switchings were performed on laser modules supplied by Marconi Caswell, and switchings were delayed by parasitic elements of laser modules. The results presented here are thus not comparable to results performed on bare laser chip and do not indicate the switching speed limit of these lasers, but conveyed information on switching time of readily available tunable laser modules.

Definition of parameters

Before presenting any results on switching time measurement, it is necessary to make clear the definition of many parameters used. In this report wavelength switching times are identified and recorded in four numbers, rise time, fall time, and delay corresponded to rise and fall transition. Rise and fall time are defined to be the time taken for power of the particular wavelength to rise from 10% to 90% of the upper state power level, and vice versa. Rise and fall delay are times taken for the switching process to begin, measured from trigger point on driving signal. (Figure 4-1)

These parameters were chosen because they offered easy and definitive mean of comparing switching speed. Digital oscilloscope used in the experiment (by LeCroy) offered automatic measurements of rise and fall time, while delay were manually measured.
Figure 4-1: Definition of rise time, fall time, and delays. Driving current signal (above) and power variation of one wavelength (lower) are shown. *Not to scale.*
CHAPTER 4. Wavelength Tuning Dynamics

4.1 Experimental Setup

Figure 4-2 shows how switching time measurements were done. Three out of four currents (gain, front grating, and phase) required to drive SG-DBR laser were provided by current sources, while rear grating current was generated by a function generator providing square wave. Laser output was then passed onto tunable bandpass filter, which allow only one wavelength component to pass through. Optical signals were then detected by a photodetector and analysed on the digital oscilloscope. Laser’s temperature was controlled at all time by feedback loop and thermoelectric coupler, to maintain temperature at 25 degree celsius.

Detailed information on components used in the experiment is presented in Table 4.1

4.2 Results

Using configuration described in previous section, only one wavelength can be analysed at a time. However, by storing the output waveform of each wavelength then display them together, the nature of wavelength switching dynamic can be study, as shown for example
4.2. Results

### Components

<table>
<thead>
<tr>
<th>Components</th>
<th>Make / Model</th>
<th>Calibration status</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function Generator</td>
<td>HP 8116A</td>
<td>In calibration</td>
<td>Rise/Fall time 10 ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Output impedance 50Ω</td>
</tr>
<tr>
<td>Digital Oscilloscope</td>
<td>LeCroy Waverunner</td>
<td>In Calibration</td>
<td>Bandwidth 500 MHz</td>
</tr>
<tr>
<td></td>
<td>LT344</td>
<td></td>
<td>Input impedance 50Ω / 1MΩ</td>
</tr>
<tr>
<td>Tunable Bandpass Filter</td>
<td>Dicon Fiberoptics</td>
<td>Not subject to</td>
<td>Tuning range 1,535-1,565 nm</td>
</tr>
<tr>
<td></td>
<td>TF-1565-0.8-FC-3.0-1</td>
<td>calibration</td>
<td>0.5-dB bandwidth 0.8 nm</td>
</tr>
<tr>
<td>Temperature Controller</td>
<td>ILX Lightwave LDT-5142</td>
<td>In calibration</td>
<td></td>
</tr>
<tr>
<td>Power Supply X 3</td>
<td>Thurlby 30V-1A</td>
<td>Not subject to</td>
<td>Output impedance &lt; 5mΩ</td>
</tr>
<tr>
<td></td>
<td></td>
<td>calibration</td>
<td></td>
</tr>
<tr>
<td>Digital Multimeter</td>
<td>Kiehley 177 / 179A</td>
<td>In calibration</td>
<td>Resolution 0.01 mA</td>
</tr>
<tr>
<td></td>
<td>Thurlby 1503-HA</td>
<td>3 months out of</td>
<td>Resolution 0.1 mA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>calibration</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1: Equipments used

in Figure 4-3. Note that dynamics of both wavelengths are identical, except for a scaling factor in power.

All semiconductor lasers being investigated here are four-sections SG-DBR lasers, with different active region geometry, these will be called laser I and laser II. Laser I is one of the early manufactured module and has buried ridge structure, while relatively new laser II has has surface ridge structure. Surface ridge structure offered higher output power but is subject to poorer thermal properties.

### 4.2.1 Switching Time

Switchings were done between two wavelengths, by changing current in rear grating section in periodic manner. Output power scanning shows that stable operating points usually lie in the middle of each modes, thus care had been taken to ensure that switchings occur between these stable regions. Wavelength pairs studied in laser I are shown in Figure 4-4.

Preliminary results suggested that delay times do not varied significantly among wavelengths pair, thus interests had been focused on investigating rise and fall time of each wavelength components. Figure 4-5 shows switching time for both kind of lasers at various wavelength separations. Each of these results is averaged over more than 500 oscilloscope’s sweeps at the particular wavelength pair. Wavelength separations used were restricted by the filter bandwidth (≈ 1 nm), and reflection peak separation of sampled grating (≈ 6-7
4.2. Results

CHAPTER 4. Wavelength Tuning Dynamics

Figure 4-3: Wavelength switching between 1540.3 and 1552.7 nm in buried ridge laser

nm) as only one current was varied.

In both lasers, switching times differ greatly between rise and fall transition of each wavelength. These fall times do not differ significantly between two lasers, but rise times are shorter in laser II by an order of magnitude. This difference in switching time is due to different packaging and bonding within laser modules, and not to the different gain section geometry. This can be confirmed as switching time measured on bare buried ridge structure laser chip was shown to be only a few nanoseconds. [41,42,43]

Results presented for laser I might suggested that switching time increase with wavelength separation, as observed in measurements on bare laser chips. Subsequent measurements, however, show that switching times do not notably increase when wavelength separation was increase up to about 20 nm. This is observed in both lasers. These results can be explained as followed: as variation of switching time versus wavelength separation occurs on nanosecond timescale, while in studied laser switching times are limit by parasitic elements to about 1 $\mu$s in laser I and 100 ns in laser II, the expected switching time variation with wavelength separation was thus rendered unobservable.

Better module design can improve switching speed to near the limit imposed by laser chips themself, as shown in results obtained from GCSR lasers manufactured by Altitun AB, with switching time about 30 ns. [44]. (Enhanced to about 5 ns with pulse pre-distortion
Figure 4-4: Wavelength map showing example of wavelength pairs being measured in buried ridge laser
4.2. Results

CHAPTER 4. Wavelength Tuning Dynamics

4.2.2 Intermediate Mode Suppression Ratio

When switching involved more than one mode hop, intermediate modes are excited. This contributes to crosstalk and thus it is interesting to see what the mode suppression ratio is. Both types of lasers had been investigate and the results are that there is no significant difference on mode suppression ratio. (See Figure 4-6) Power ratio between the higher of start/stop mode and the unwanted intermediate mode is 28.9 dB and 29.8 dB for buried ridge and surface ridge laser, respectively. Note that this is for particular pair of wavelength

Figure 4-5: Measured switching time of (a),(b) buried ridge laser and (c),(d) surface ridge laser, versus wavelength separation

...
4.2. Results

CHAPTER 4. Wavelength Tuning Dynamics

Figure 4-6: Mode suppression ratio during wavelength switching

and the switching current rise time is about 7 ns.

4.2.3 Effect of electronics impedance

It was shown that parasitic elements and electrical bonding within laser modules have great


effect on switching time. It is also equally important to match impedance of driving circuit

and the device itself to optimize electrical connection and thus switching speed. To choose

the best value of series resistance to use, measurements were done on the the dependency

of switching time on series resistance, and results are shown in Figure 4-7.

These measurements were done on a SG-DBR laser module, by switching laser’s wave-

length between 1538.4 nm and 1544.5 nm at the rate of 20 kHz, up-conversion means

transition from shorter wavelength to the longer, and vice versa for down-conversion. Driv-

ing current are in the form of square wave, with amplitude and DC offset adjusted to give

roughly the same current step when used with different series resistor.

Tradeoff between forward and backward switching time can be obviously seen and value

of series resistance about 50 Ω gives reasonable compromising.
4.3 Pulse Pre-distortion technique

In most type of tunable semiconductor lasers, including SG-DBR lasers, the ultimate lower limit of switching time is impose by carrier lifetime in active region. This is an intrinsic property of the material and cannot be easily changed.

However, carrier dynamics in active region, and thus switching characteristics, can be manipulate by changing the way lasers are driven. It is known that switching time can be reduced by employing pulse pre-distortion technique. [45, 12] This was originally done using two laser drivers and differentiator (Figure 4-8), but this is difficult to use with multi-wavelength switching as different differentiator characteristics will be required for each wavelength pairs. Fukashiro et al. [44] suggested driver unit based on digital-to-analog converters (DACs) with current sources to produce pre-distorted current pulse. This provide configurable driver capable of fast-switching between any desired wavelengths.

The pulse pre-distortion technique discussed above has only been demonstrated on GCSR type lasers by switching current applied to coupler [45] or reflector [12,44] section, but should apply generally to carrier injection tuning of any semiconductor lasers.

Pulse pre-distortion technique had been implemented with both lasers studied, and by varying the overshoot size and duration some better performance had been observed. This enhancement of switching time is, however, not as significant as in other works [45,44], and
the origin of this finding will be discussed.

Driving used in this experiment has rise/fall time of about 10 ns, which is on the same order as switching times reported. [41, 42, 44] It is thus clear that faster driver is needed to obtain better performance. The driving circuit also already exhibit overshoot characteristics, which could be from capacitance in the circuit. This internal overshoot has duration of about 0.5 $\mu$s. This explained why switching time enhancement was not observed when pulse pre-distortion technique was implemented with laser II, as 0.5 $\mu$s is much longer than the laser’s rise time. (about 0.1 $\mu$s) All these indicated that with better driving unit, shorter switching time should be achievable.

Another benefit offered by pulse pre-distortion technique is reduced Mode Suppression Ratio during wavelength switching. [44] This phenomena was observed and result was shown in Figure 4-9. Mode suppression ratio was increase by about 3.5 dB.

4.4 Thermal drift

So far, only electronic effects had been considered, this is because the time scale imposed by packet-switched networks are much smaller than that of thermal effects of lasers. However, it has to be noted that switching performed in this project only occurs between two wavelengths and thermal equilibrium had been reached. In real world, traffics come with various characteristics, e.g. gaussian, random inhomogeneous traffic, or bursty traffic, and
these will have different effects on longer-timescale thermal properties of tunable lasers, and thus their tuning characteristics. Cares had to be taken in the control of these lasers, to ensure correct functionality over time and changing traffic.
Chapter 5

Conclusion

Comparing the switching speeds measured and the requirement for packet switching, it can be seen that the modules tested do not offer the desired performance. However, the ultimate limit of switching speed had not yet been reached, and wavelength routing with tunable transmitters had great potential in eventually deliver switching on packet-by-packet basis. Many switch and network configurations had been proposed to date, and demonstrations on small scale networks show promising results.
Appendix A

Arrayed Waveguide Grating devices

This appendix on arrayed waveguide grating followed closely those treatment in [2]. Theoretical results are presented for understanding of how the device perform when used as wavelength router. Readers are referred to reference given in Chapter 8 of [2] for more detailed discussion on applications and performance of AWG devices.

Star coupler couples light from any input to all output port and, ideally, split the power evenly. The device consist of array of input and output waveguide (fiber) connected by a waveguide slab. (Figure A-1)

And Figure A-2 shows, AWG form by two star couplers connected by number of waveguides. If these waveguides has identical length, AWG would just direct signal from \( n_{th} \) input port to the \( n_{th} \) output port. However, if these waveguides has linearly increasing
length, the waveguides can act as grating by distorting the wavefront emerge from them. The waveguide itself exhibit certain dispersion, thus the path different experienced by different wavelengths are not the same, and the amount that wavefronts are distorted therefore varied.

![Arrayed waveguide grating](image)

Figure A-2: Arrayed waveguide grating

With suitable design, AWG can perform as a wavelength router by directing signal from input to output port according to wavelength and input port number. AWG can be of miniature dimensions and integration with semiconductor lasers had been demonstrated. The maximum number of port to date is to device produced at NTT, Japan, with 256 input and output ports, and 25 GHz channel spacing. [10]

Another interesting property of AWG router is that wavelength are wrapped around, i.e. wavelength $\lambda_i$ and $\lambda_i + \Delta \lambda_{FSR}$ will be route to the same output port, where $\Delta \lambda_{FSR}$ is the free spectral range of the device and is equal

$$\Delta \lambda_{FSR} = \frac{\lambda^2}{n_g l}$$  \hspace{1cm} (A.1)

where $n_g$ is the group index and $l$ is the path length different in the waveguides.
Bibliography


